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CROSSED-PLANE LASER IMAGING
OF
PREMIXED TURBULENT COMBUSTION PROCESSES

DAAD19-99-1-0324
F. C. Gouldin
Cornell University, Ithaca, NY 14853

Overview

The objective of our research is to measure, using crossed-plane imaging, normal vectors and the instantaneous thermal structure of flamelets in premixed turbulent flames. Data for surface normal vectors can be used to calculate important quantities such as Σ, the flamelet surface density. Σ is a measure of the wrinkling of the flamelet surface and is proportional to the rate of product formation per unit volume in the flame, $<w>$, which appears as an unclosed term in premixed flame models and is related to the burning intensity. Flamelet thermal structure data can be used to estimate the constant of proportionality between $<w>$ and Σ. Instantaneous flamelet normals have been measured in three dimensions using crossed-plane imaging via either laser tomography or planar laser induced acetone fluorescence. We are now exploiting crossed-plane imaging for flamelet normal measurements in different burners and over a range of conditions. In additional we are developing crossed-plane Rayleigh imaging in order to measure temperature gradients within flamelets and thereby to determine their thermal structure. Through measurements of flamelet normal and thermal structure we can estimate $<w>$.

I. Introduction

Premixed turbulent combustion has a broad range of practical applications, from powering the vehicles we drive to proposed low emissions jet engine combustors. In many cases, conditions fall within what is called the flamelet regime in which reactions are confined to thin sheets, called flamelets, separating regions of reactants and regions of products. For these conditions, the burning intensity is related to the degree of wrinkling of the flame: the wrinkling serves to increase Σ and hence $<w>$. Σ can be expressed as a function of the probability density function, PDF, of the flamelet surface normal vector, $\underline{N}$, and the flamelet crossing density, n_c. Thus it can be determined by crossed plane imagining measurements of $\underline{N}$ and n_c. Furthermore, the constant of proportionality, the mean rate of production formation per unit of flamelet area, relating Σ and $<w>$ can be estimated from data on the thermal structure of the flamelets.

Crossed-plane imaging was developed in 1997 [1] at Cornell with ARO support to provide, for the first time, data for $\underline{N}$ in three dimensions. The first measurements were performed to validate the technique and measure $\underline{N}$ in laboratory flames and to find $\underline{N}$ in a research spark-ignition, SI, engine [1-3]. Repeated measurements of $\underline{N}$ allowed its PDF to be determined. It was found that, for laboratory V and engine flames, the PDF of $\underline{N}$ has a simple form depending on a single parameter, ζ. In turn crossing density data, n_c, were used with the PDF of $\underline{N}$ to determine Σ and mass burning rate information in V and engine flames. More recently, the technique has been applied to examine the dependency of the PDF of $\underline{N}$ on Markstein number, *Ma* [4]. It was found for the flames studied that the dependency is very weak.

In the past year, we have investigated the use of single-plane imaging to find the fit parameter, ζ, in flames where the $\underline{N}$ PDF form is the one found in V-flames and engine flames. We have studied the effect of engine cycle-to-cycle variations, CCV, on our engine measurements and have worked on crossed-plane Rayleigh imaging.

II. Crossed-Plane Imaging

Crossed-plane imaging is an extension of imaging techniques such as laser tomography (LT), planar Rayleigh imaging (PRI) and planar laser induced fluorescence (PLIF). In LT, oil droplets are added to the reactants and are consumed within the flamelet. A pulsed laser sheet is propagated through the flame, and an image is recorded normal to the laser sheet. The image contains bright reactant regions, where light is scattered from the oil droplets, and dark product regions where there is no scattering. The flamelet is located by the interface of the bright and dark regions, and fitting this interface provides two dimensional information about $\underline{N}$. PRI and PLIF can be used in much the same way as LT in crossed-plane imaging, except that the laser frequency must be chosen such that either molecular fluoresce (PLIF) or molecular scattering (PRI) is excited. In either case, lines of constant fluorescence or constant scattering can be identified in the illumination plane. Crossed-plane imaging involves simultaneous imaging from two orthogonal, pulsed laser sheets that intersect along a line, the measurement line. In the case of crossed-plane tomography, at points where the measurement line intersects the flamelet curves identified in the recorded images, tangent vectors to these curves are tangents to the flamelet surface. Thus the cross product of two such tangents is parallel to $\underline{N}$ in three dimensions. In crossed-plane PLIF and crossed-plane PRI contours of constant light intensity can be determined. Tangents to an iso-contour are also tangents to the corresponding iso-concentration surface in the case of PLIF or iso-thermal surface in the case of RRI. Thus along the line of intersection of the two illumination planes pairs of iso-surface tangents can be determined and their cross product used to find iso-surface normals. We are preparing now to use crossed-plane PRI to find iso-thermal surface normals and temperature gradients using the relationship between the temperature gradient and the directional derivative of the temperature.

III. Single Plane Measurements of the Fit Parameter.

The most significant discovery so far from our crossed-plane imaging measurements has been that the PDF of $\underline{N}$ appears to have a universal form: the surface weighted PDF of $\underline{N}$ is

$$P_s(\phi,\theta)\,\sin\phi \mathrm{d}\phi \mathrm{d}\theta = A\,\exp(-\phi^2/\zeta^2)\,\sin\phi \mathrm{d}\phi \mathrm{d}\theta \qquad (1)$$

when written in spherical coordinates with the polar axis aligned with the mean of the $\underline{N}$, $\langle\underline{N}\rangle$, or equivalently with the normal to a mean progress variable constant ($\langle c\rangle$) surface, $\underline{N}_{\langle c\rangle}$ [2-4]. ϕ is the polar angle, θ is the azimuthal angle, and A is a normalization constant.

It is desirable when possible to extract three-dimensional $\underline{N}$ data from single plane, two-dimensional image data because of the simplicity of such measurements. Single plane imaging allows measurements of flamelet orientation at any point along the flamelet curve, while in crossed-plane imaging, which involves simultaneous orthogonal, single plane measurements, orientation data can only be obtained along the line of intersection of the two illumination planes.

To evaluate the potential for single plane measurements we determined the relationship between the PDF of $\underline{N}_{yz}$, the projection of $\underline{N}$ onto a plane perpendicular to the <c> constant surfaces and the PDF of $\underline{N}$ given in Eq. (1) [5]. We found that because of the rotational symmetry about the polar axis three-dimensional information can be obtained from two dimensional image data if the imaging plane contains the polar axis, which it does if aligned

perpendicular to the <c> constant surfaces. The angle between $\underline{N}_{yz}$ and the polar axis is defined as α. Computations were performed to generate the PDF of α, P (α), from the crossing-weighted PDF of $\underline{N}$. The resulting α PDF is found to depend on a single fit parameter γ that is a unique function of ζ, Figure 1 [5].

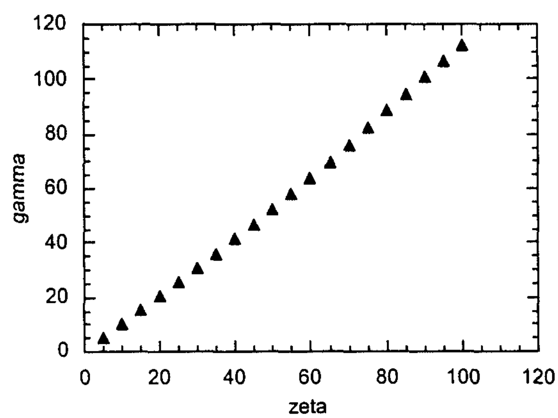

Figure 1. γ, the PDF fit parameter of α generated over a range of ζ, the PDF fit parameter of $\underline{N}$.

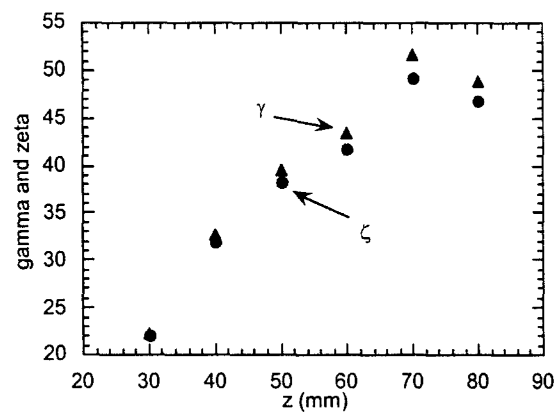

Figure 2. Variation of measured γ and calculated ζ with increasing downstream distance, z.

To demonstrate the utility of this relationship, the evolution of ζ, and γ with increasing downstream distance in a methane-air V-flame was studied. α was measured by imaging a single, vertical plane perpendicular to the V-flame stabilizing rod. <c> constant surfaces for a V-flame are planes containing the stabilizing rod; therefore the normal to a <c> constant surface, the polar axis, is within the imaging plane described above. The PDF of α and the two-dimensional fit parameter γ were estimated from repeated measurements. Using the relationship between γ and ζ determined computationally (Fig. 1), ζ was obtained from γ. Six positions were studied, beginning at 30 mm downstream from the stabilizing rod with measurements taken in 10 mm increments. These measurements [5] show that ζ initially increases linearly with z close to the stabilizing rod, while the relationship becomes nonlinear further downstream, Figure 2. This trend seems reasonable. While u' decreases with downstream distance, wrinkling is damped close to the flame stabilizing rod and is expected to grow downstream.

IV. SI Engine: Study of Cycle-to-Cycle Variation (CCV) Effects

In Reference 3 we reported SI engine, crossed-plane acetone PLIF measurements of $\underline{N}$ and the use of these $\underline{N}$ data to estimate mass burning rates. The mass burning rate estimates were compared to values obtained from pressure data and found to be quite high. In the last year we reanalyzed the image data for evidence of CCV and its possible influence on these estimates [6].

Evidence for the presence of CCV and its effects were found in the imaging data. Determination of an effective turbulent flame area was found to be affected by CCV, however these CCV effects did not result in an over-prediction of the area, and therefore burning rate, as expected. Other possible factors contributing to the discrepancy in burning rate values based on $\underline{N}$ data include the choice of the surface that is used to define the turbulent flame area and underestimation of the perturbation of flamelet structures by turbulence.

V. Crossed-Plane Rayleigh Imaging

At low levels of turbulence the flamelet is wrinkled by turbulent flow fluctuations thereby increasing Σ, but its internal structure is not perturbed. As the turbulence intensity increases perturbation of the flamelet structure increases, first in the low temperature preheat zone and then, as the intensity continues to increase, all over. Finally at high turbulence the flamelet can be quenched locally. To help quantify the perturbing effect of turbulence and how it increases with turbulence intensity we will be making crossed-plane Rayleigh imaging measurements.

To perform these measurements we are using a frequency doubled Nd: YAG laser and two intensified CCD cameras. Rayleigh scattering is proportional to the molecular number density and in the case of lean methane-air mixtures the scattering cross section of the gases is a weak function of c. Thus by PRI we will be able to identify using the ideal gas law iso-thermal contours in the recorded Rayleigh scattering images. Then with crossed-plane imaging we will be able to find along the line of intersection of the laser illumination planes normal vectors to iso-thermal surfaces. Directional temperature derivatives along this line can also be determined, and the combination of surface normal and directional derivative used to find the temperature gradient.

Our plan is to make crossed-plane Rayleigh measurements in a variety of flames and find T and grad T versus the progress variable. Then to assess the degree of flamelet structure perturbation we will compare measured values of T and grad T to ones calculated for unperturbed flames based on GRIMech chemistry.

To date we have set up the Rayleigh imaging system and have made measurements on a laminar flame. Measured and calculated temperature profiles have been compared and good agreement found.

VI. Summary

Crossed-plane imaging was developed to measure flamelet normal distributions and has been used in V-flame and engine measurements. The PDF of the normal takes a simple form with a single parameter. We have shown how single plane measurements can be used to find this parameter and using this approach measured the spatial variation of this parameter in V-flames. Review of our engine data shows effects of CCV. Progress in developing crossed-plane Rayleigh scattering is reported. High quality single image data have been obtained. Crossed-plane measurements will begin soon. For the next year we will pursue flamelet normal and flamelet thermal structure measurements and thanks to a DURIP award add stereo-PIV to our measurement capabilities.

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